A methodology for the classification of convective structures using meteorological radar: Application to heavy rainfall events on the Mediterranean coast of the Iberian Peninsula

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Abstract. During the period 1996–2000, forty-three heavy rainfall events have been detected in the Internal Basins of Catalonia (Northeastern of Spain). Most of these events caused floods and serious damage. This high number leads to the need for a methodology to classify them, on the basis of their surface rainfall distribution, their internal organization and their physical features. The aim of this paper is to show a methodology to analyze systematically the convective structures responsible of those heavy rainfall events on the basis of the information supplied by the meteorological radar. The proposed methodology is as follows. Firstly, the rainfall intensity and the surface rainfall pattern are analyzed on the basis of the raingauge data. Secondly, the convective structures at the lowest level are identified and characterized by using a 2-D algorithm, and the convective cells are identified by using a 3-D procedure that looks for the reflectivity cores in every radar volume. Thirdly, the convective cells (3-D) are associated with the 2-D structures (convective rainfall areas). This methodology has been applied to the 43 heavy rainfall events using the meteorological radar located near Barcelona and the SAIH automatic raingauge network.

1 Introduction

During the period 1996–2000, a significant number of catastrophic floods (Llasat et al., 2002) and extraordinary floods (Rigo and Llasat, 2000; Rigo et al., 2001) affected the Northeast of Spain. A flood event is considered catastrophic (Llasat and Puigcerver, 1994; Llasat et al., 2003) if it reaches high accumulated rainfall values (exceeding 200 mm), if more than 100 mm are accumulated within a region exceeding 2000 km^2, and if there is material damage with complete destruction of some infrastructure or buildings. Usually, there is also some loss of human life. If those thresholds are not reached but the overflow of the river causes some damage (material or human), the event is classified as extraordinary. This kind of classification is useful in order to have a common classification of flood events dating back some centuries (Llasat and Barriendos, 2001).

Generally, catastrophic flood events are connected with certain well-known meteorological situations (Ramis et al., 1994; Llasat, 1987; Llasat and Puigcerver, 1994; Llasat, 1997; Llasat et al., 1999, 2000, 2001; Jansà, 1990, 1997), where high amounts of precipitation are accumulated at many points of the region. The conceptual model (Llasat and Puigcerver, 1994) shows during the previous days a long anticyclonic situation over the Mediterranean, which promotes the formation of a Mediterranean air mass (Jansà et al., 1995, 1996) and the accumulation of water vapour. Usually, the presence of any Mediterranean low or a convergence line organizes the different air currents as well as internal low frontal boundaries. The intersection between the tip of a warm-wet flow and a thermal-humidity boundary is the most likely place for attaining or releasing the convective instability and for the development of large convective clouds producing heavy rain. If the situation remains quite stationary the accumulated rainfall can reach very large amounts (i.e. see 28 September–5 October 1987 in Catalonia, in Ramis et al., 1994). Another possibility is that the convergence line is replaced by a mountain barrier that blocks and forces the ascent of the warm-wet flow (i.e. see 6–8 November 1982, northeast of Spain and south of France in Llasat, 1993). Usually, both variants appear in combination and it is difficult to assess the contribution of each factor, bearing in mind the synergetic effects between them.

However, there are many local events that affect mountainous or coastal regions. In these cases, high rainfall rates are registered over a short period of time (Llasat, 2001; Carretero et al., 2001). As a consequence, extraordinary floods produced by the overflowing of rivers, tributaries or wadis are produced in small catchment areas.

Both cases, catastrophic and local heavy rainfall events are important: the first one because of the considerable damage that occurs, while the second case is more frequent (local

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Table 1. An event has been considered as heavy rain if it exceeded any one of the rainfall thresholds listed here.

Rainfall threshold
100 mm/24 h in at least one raingauge
60 mm/24 h in 5 or more raingauges
35 mm/1 h in one or more raingauges
200 mm in the entire event, in at least one raingauge

floods are produced in Catalonia every year). Thus, in order to consider all types of events (from the short and intense ones to those that affect extended areas with high values of accumulated rainfall) it is necessary to include different thresholds of rainfall intensity and accumulated values. In this paper, four thresholds have been applied (Table 1) to a 5-min rainfall series (1996–2000) with the purpose of identifying all the events occurring during this period. Thresholds have been selected taking into account those considered by the meteorological services of the region: the “Instituto Nacional de Meteorología” (INM) or National Weather Service of Spain and the Meteorological Service of Catalonia (SMC). Catastrophic floods are a specific case related with heavy rainfalls. In those cases, besides to accomplish one or more of these threshold criteria, they have attaining these other ones proposed in the first paragraph of this Introduction.

Once the rainfall intensity and accumulated values have been obtained, those events that satisfied at least one of the previous conditions have been identified as “heavy rainfall events” and their “convective structures” have been analyzed using the meteorological radar.

There exist many methods for analyzing convection using radar imagery. In general, most of them (Agarwal and Anagnostou, personal communication; Steiner et al., 1995; Biggerstaff and Listemaa, 2000; Collier, 1989; Johnson et al., 1998; Hand and Conway, 1995; Wilson et al., 1998; Sánchez-Diezma, 2001) are based on background-exceeding techniques: they select one (or more) reflectivity value, which is considered as the minimum value that a “convective” pixel must have. Then, all the pixels that exceed that threshold are identified as associated with precipitation due to convection. The main difference between the algorithms lies in the point of view used to analyze convection. In general, it is possible to classify the algorithms into two types: those methods that consider precipitation type (classifying it as “convective” or “stratiform”) as against those oriented towards cloud structures (identifying different states of the clouds). Quite often, the hydrological algorithms use only the lowest (PPI or CAPPI) radar level. On the other hand, the meteorological procedures use all the radar volume. It thus seems obvious that the main differences will appear in the time of running of the program (obviously, the 2-D algorithms are quite considerably faster than 3-D ones) and the accuracy of the results (better results in the case of 3-D methods).

Table 2. Characteristics of the INM meteorological radar in Barcelona, which has been used in this work.

Mode	Normal	Doppler
Range	240 km	120 km
First elevation altitude	0.5°	0.5°
Number of levels	20	8
PRF	250 Hz	900/1200 Hz
Frequency	5600–5650 MHz	
Polarization	Horizontal	

In this paper, an attempt at combining two of those methods is presented. The first is adapted from the 2-D algorithm of Steiner et al. (1995), and the second is based on the Storm Cell Identification and Tracking (SCIT) method, a 3-D algorithm created by Johnson et al. (1998). The main goal of merging the two procedures is to obtain an improved relationship between convective cells and the type of precipitation (stratiform/convective), and also, to improve the methodology for the classification, tracking and nowcasting convective structures.

The organization of the paper is as follows: Firstly, Sect. 2 describes the database used in this study. Section 3 presents the methodology proposed for analyzing convection in heavy rainfall events. Section 4 shows initial results for the different types of convective structures present in various cases of heavy rains in the region. Finally, Sect. 5 summarizes the results obtained in this research.

2 Database and area of study

Observations were carried out in the Internal Basins of Catalonia (hereinafter, IBC), a region that is situated in the northeastern part of the Iberian Peninsula (Fig. 1). The IBC constitutes part of the fluvial network of Catalonia, and are competency of the Government of Catalonia and their management is entrusted to the Catalan Water Agency. The total area of the region is close to 16 000 km^2. Some geographical features of the region are:

- The existence of three mountain ranges: the Pyrenees, which are situated in the northern part and have peaks that rise to 3000 m; the Pre-Littoral range, which runs across the area from SW to NE, with some altitudes exceeding 1 500 m; and, finally, the Littoral range, the one closest to the coast and with some altitudes of about 1000 m.

- Only two rivers (Ter and Llobregat) have basins that exceed 3000 km^2. Most of the basins in the region have a very small area and high slopes, due to the complex orography.

In this paper, all the rainfall events that occurred in the IBC over the period 1996–2000 have been analyzed in order to select those heavy rainfall events. The rainfall network of the

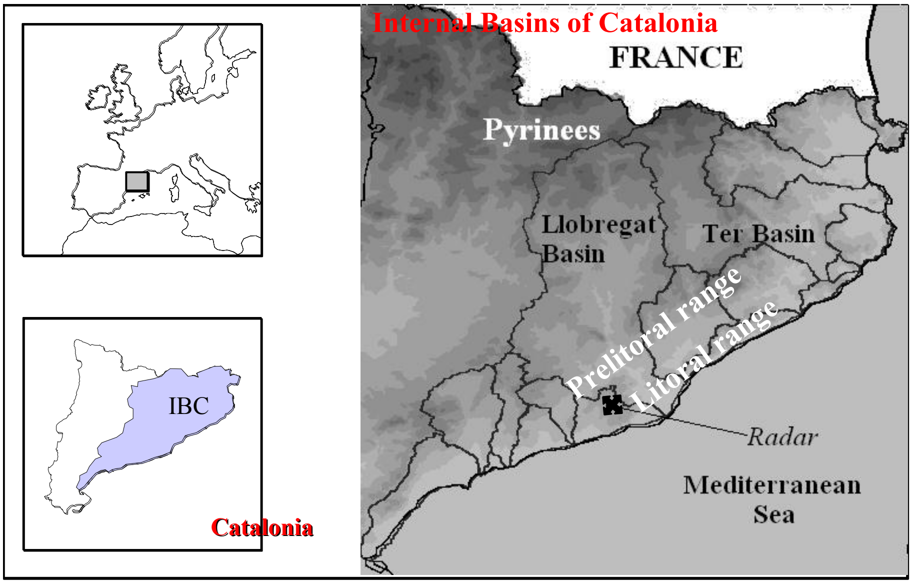

Fig. 1. Geographical location of the Internal Basins of Catalonia. The cross marks the location of the meteorological radar used in this analysis.

SAIH ("Sistema Automático de Información Hidrológica", that means Automatic System of Hydrological Information) of the IBC has provided the pluviometric data. 126 automatic tipping buckets distributed over this region comprise this network that gives continuous information on accumulated rainfall at intervals of 5 min. Forty-three heavy rain events have been detected in accordance with the four thresholds described in Table 1.

The next step of the study has been radar data retrieval. The analysis has been carried out using the data from the meteorological radar of Barcelona of the INM. This radar is situated near Barcelona city, on Puig de les Agulles, at 612 m a.s.l. Its properties are shown in Table 2. The mode Doppler has not been used in this analysis because it was not operative during a great part of the time period analyzed here.

The total number of images (an image has been considered as the complete radar volume for a selected time) retrieved has been 5000 for 31 events (various problems prevented images being obtained in 12 cases). It is important to remark upon the fact that the selected images are related with periods of heavy precipitation in the region. Thus, no images have been selected with rainfall over the sea or regions where rain gauges have not been available.

Images have been slightly corrected previously by the INM. (Sánchez-Diezma, 2001), using the following procedure. Firstly, the main ground echoes have been eliminated using a ground clutter mask created previously. Secondly, a procedure has been applied in order to convert the polar coordinates of the primary images to Cartesian coordinates. The last step of the correction procedure has been removal of those pixels with reflectivity values under 12 dBz. The objective is to eliminate those pixels which could not be considered as "rainfall" ones and, on the contrary, could introduce a lot of noise and calculus difficulties. This threshold has been selected due to the fact that the corresponding rain rate value, using the Marshall-Palmer (1948) Z/R relationship, is close to 0.1 mm/h (SAIH rain gauges accuracy is 0.1 mm). Once the image had been corrected, it has been ready to be treated using the convection analysis process.

3 Methodology proposed

First of all, many algorithms developed to study the convection based on the meteorological radar information (Steiner et al., 1995; Biggerstaff and Listemaa, 2000; Johnson et al., 1998; Hand and Conway, 1995; Wilson et al., 1998) have been analyzed in order to select the most suitable ones for operational requirements. Two of them have been selected to identify, characterizing, tracking and making a short-range forecast (nowcast) of convective systems. The first one (Steiner et al., 1995) has been adapted to the area of Spain and it has been applied to identify regions of convective precipitation in the lowest level. This 2-D algorithm has been selected in front of other algorithms because it gives the optimal difference between time running and values obtained. The second algorithm used here (Johnson et al., 1998) attempts to identify convective cells that produce high amounts of rainfall, using all the radar volume (3-D). Both procedures have been combined with the aim of yielding more information about the convective structures. This method does not include the radar imagery correction. For this reason, it has to be applied over the corrected radar images (Fig. 2).

3.1 First step: identification of the convective structures

Steiner et al. (1995) proposed a 2-D algorithm known as the SHY (Steiner-Houze-Yuter, author's name) algorithm. This algorithm has been adapted to the Spanish region by the STAP ("Servicio de Técnicas APlicadas", that means Service of Applied Techniques) of the INM and GAMA (Group

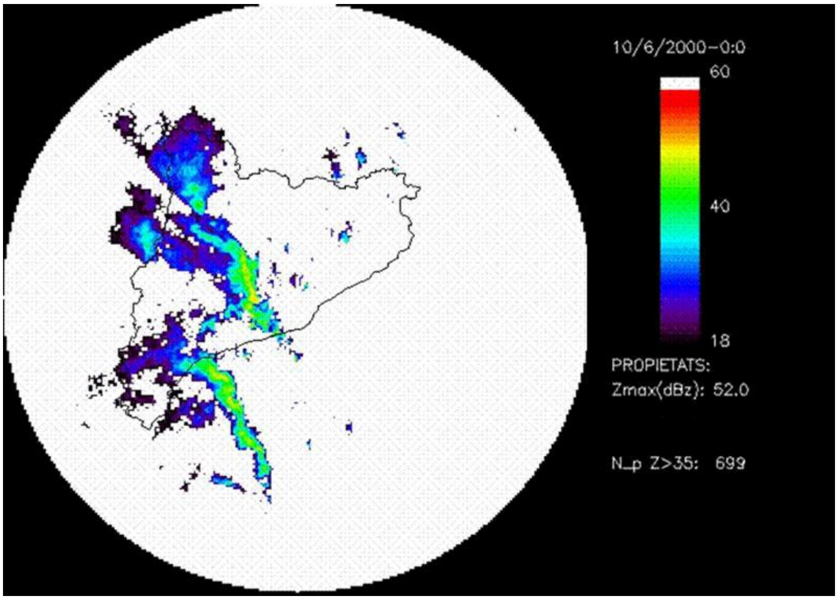

Fig. 2. Lowest PPI (Plan Position Indicator) of the corrected volume image (10 June 2000 at 00:00 UTC). Main properties of the radar image showed here are: Z_{max}=52.00 dBz, Z_{med}=7.55 dBz and number of pixels with Z>35 dBz=699. The example corresponds to the 10 June 2000 event (00:00 UTC).

Table 3. Different requirements that have been used for identifying convective pixels in the 2-D algorithm.

Procedure name	Requirements for "convective" pixels
Reflectivity threshold	$Z>43$ dBz
Background reflectivity (Z_{bg})	$Z - Z_{bg} > (1/a)^* \cos(\pi Z_{bg}/2^* b)$
Position	The pixels adjacent to a convective pixel are considered as convective.

for Analysis of Meteorological hazards) of the Department of Astronomy and Meteorology of the University of Barcelona (Rigo and Llasat, 2002a, b; Martín et al., 2001, 2002; Martín and Carretero, 2001).

This algorithm considers only the PPI or the lowest CAPPI, and takes into account the horizontal distribution of convective and stratiform precipitation. The adapted process to identify convective pixels considers three requirements that are independent one from another (see Table 3). One pixel is considered "convective" if it verifies at least one of them.

Firstly, a reflectivity threshold has been applied in order to obtain pixels that could be considered as "convective" with a high confidence. Some previous studies (Sánchez-Diezma, 2001; Llasat and Rigo, 2002) have determined that this reflectivity threshold oscillates between 40 and 45 dBz, depending on the methodology used and the meteorological situation. This first point is associated with the fact that, generally, convective rain rates are more intense than stratiform values (Llasat, 2001). Secondly, a pixel that not exceeds the "convective" threshold has been labelled as "convective" if the difference between its value and a mean value of its background exceeds a considered function (Sánchez-Diezma, 2001), which depends on the background reflectivity and the radar characteristics. This second point considers the strong gradient observed in areas where convective precipitation is produced. The third requirements considers that if they are some "convective" pixels adjacent to the analysed pixel, this last could be considered as "convective". This last requirement has been applied in order to consider as convective those pixels located in the border of the convective area that does not accomplish the previous criteria but that are part of the convective system. Once the three requirements have been applied to all the pixels, those that not verifies anyone of them have been classified as "stratiform" (Fig. 3).

3.2 Second step: identification of the convective cells

The second algorithm, developed by Johnson et al. (1998), has been used to detect 3-D convective cells. This method is known as SCIT ("Storm Cell Identification and Tracking"), and has also been adapted to the area of Spain by the STAP and the GAMA groups (Carretero et al., 2001; Rigo and Llasat, 2002a, b). Like the 2-D procedure, this adapted procedure has been divided into different parts.

Firstly, it aims to select in each level those pixels (labelled as "convective") that exceed one of the various reflectivity thresholds (30, 35, 40, 45, 50, 55 and 60 dBz), in order to find the cell's core. These different thresholds have been considered in order to look for all the cells (although they could be in different stages of evolution) in all the levels. Then, for each region with "convective cores", the method selects the zones that have the same reflectivity value as the core for 6 pixels or more, that is 24 km^2 (Martín et al., 2001) This size threshold has been imposed in order to eliminate regions of anomalous echoes (small size) and to select the most important cells. If there have been fewer than 6 pixels

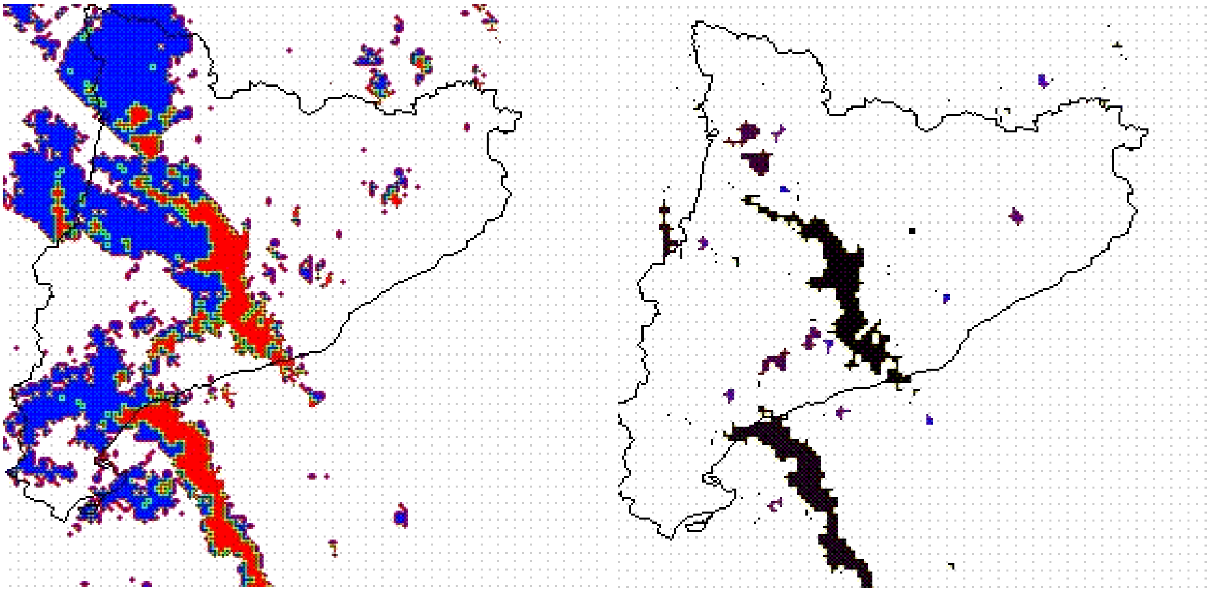

Fig. 3. Example of application of the 2-D algorithm. **(a)** Convective system, in which red areas are “convective” rainfall regions, while blue means “stratiform” rainfall; **(b)** convective precipitation areas have been isolated. The example corresponds to the 10 June 2000 event (00:00 UTC).

for one reflectivity level, the method automatically selects the next reflectivity value. The pixels that do not reach the core threshold can not be considered as a part of the “convective core”. Finally, if the cell has been detected in more than one level, the algorithm takes it as a valid convective cell (Fig. 4). If a gap of one level exists, the algorithm considers the two nearest cells in the vertical as being the same.

It is important to notice here that a convective cell is considered as the main core (or where the reflectivity has the strongest values) in the radar volume, while in the 2-D algorithm the idea is to detect areas where convection develops at low levels, producing heavy rainfall. Also, the data used present another difference: only the lowest level has been used for the SHY modified method, while the SCIT modify algorithm considers all the radar volume.

3.3 Third step: Characterization of convective structures

Once both types of convective structures (2-D and 3-D) have been identified, the procedure calculates some features in order to characterize the 2-D and 3-D structures separately. These characteristics provide knowledge of the position, the size, the shape and the intensity of each structure. In the case of the convective cells, due to their volumetric shape, other features relative to the vertical parameters have been obtained: heights of the top and base of the cell, echotop, or tilt between base and top levels.

The position has been calculated by means of the centroid, which is considered as the mass center using the Eq. (1). For the 2-D structures, the centroid is only calculated by means of the x_c and y_c, values at the lowest PPI, meanwhile for the 3-D structures the vertical coordinate (z_c) is also determined.

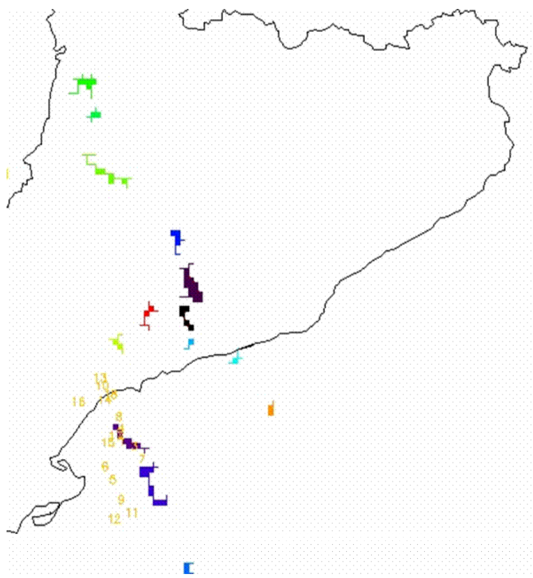

Fig. 4. Example of application of the 3-D algorithm. Shaded regions are convective cells (the figure is the projection of the lowest level of each cell detected). The example corresponds to the same image as the previous figures (10 June 2000 event at 00:00 UTC).

$$x_c = \frac{\sum_i x_i Z_i}{\sum_i Z_i} \tag{1}$$

In the case of the convective rainfall regions (2-D structures), they are characterized as ellipses using the Riosalido et al. (1997) method. Then, the area and the maximum axis determine its size; the shape is obtained by mean of the eccentricity (indicating if the convective structure has a linear organization or not). For the convective cells (3-D structures), size and shape are characterized by the area in each level and the cell volume.

Finally, the intensity is calculated using different parameters: maximum and mean reflectivity, Vertically Integrated Liquid (VIL, Collier, 1989) and VIL density. This last parameter is especially useful to identify the probability of hailstorms using the 3-D method.

All these features are stored with two future goals: operational (the forecasters have all the previous information of a cell to asses its possible evolution) and to create a database with the required information to do a climatology of convective systems and cells and to improve nowcasting models.

3.4 Fourth step: integration of the convective structures and convective cells

Once the characteristics have been determined, it is possible to integrate the 2-D and 3-D results in order to associate each cell with a specific convective system (in this case, convective system means any convective structure more or less developed, and not necessarily in the category of a Mesoscale Convective System). The integration has been done considering the location of the convective cell centroid and the total area of the 2-D structure. In general, all the 3-D structures belong to a large surface structure, but there exist two cases that this situation could not occur. The first situation is produced when the convective precipitation is associated with old convection (Steiner et al., 1995), and the vertical development has little importance. Then, the 2-D convective rainfall region does not contain any convective cell and it is converted back into a "not-well-defined" precipitation region, or an "old-convective precipitation region", depending on the distance to the radar. The farthest structures are classified with the first name and those structures placed closed to the radar are identified with the second one. The second situation shows a convective cell only detected in high levels. This second case could be associated with the development stage of the cell. However, in many cases, this is due to the large distance of the cell to the radar, and low levels are not well identified.

3.5 Classification of precipitation structures

In order to classify the different kind of precipitation structures (Fig. 5), the first work done has been to determinate the degree of organization that has predominated in each radar image. Then, once all the precipitation structures have been identified, their distribution, size, duration and relative position between the stratiform and convective zones have been analyzed for each radar image, using the 2-D method. Taking into account those parameters and some previous works (Parker and Johnson, 2000; Schiesser et al., 1995; Doswell et al., 1996; Weisman and Klemp, 1986), the next classification has been proposed:

- Mesoscale Convective System (MCS): a precipitation structure could be identified as MCS when its major axis has a length equal or above 100 km during 3 h or more, and a minimum of a 30% of the area covered by it in each image can be associated to convective rainfall. A MCS has been classified depending on the position of its stratiform region in relationship to the convective area, and depending on the organization of the convective region. Then, they could be divided in well-organised systems usually lineally, and poorly-organised systems, or clusters of convective structures (CLU). The first type could be divided in TS (with trailing stratiform area), LS (leading stratiform region), and NS (with practically no stratiform precipitation). A specific case of the NS class would be when the stratiform region is placed in a flank of the convective line and its movement is parallel to this one of the convective region.

- Multicell systems (MUL): if the rainfall structure has a convective area exceeding the 30% of the total echo region, but does not meet the condition about time and size for being for an MCS.

- Isolated convection (IND): when small scale, independent, and separated convective structures are identified

- Convection embedded in stratiform rainfall (EST-EMB): a stratiform region with some convective nucleous. The area covered by the convective precipitation does not exceed 30% of the total echo region.

- Stratiform (EST): when convective precipitation does not exist or does not exceed 3% of the total echo area

Supercell structures have not been considered here because their main feature is the detection of a mesocyclone (Doswell and Burgess, 1993), feature only detectable by using Doppler wind information (in this study only reflectivity volumes have been analysed). Each image has been labelled on the basis of the most important kind of structure identified in it. When two or more structures have been identified in the same radar image, only one of them has been recorded. The selection criterion has been the following: 1) MCS, 2) EMB-EST, 3) MUL, 4) IND, 5) EST. Then, for instance, if there exists a multicell structure and a stratiform region only the first one is considered. Special priority has been given to the MCS and, for this reason, when in one image there appear two or more MCSs, then all of them have been considered. In some cases, a MCS can change its characteristics during its life-cycle (i.e. MCS-TS to MCS-NS, or, at the end of its life, to EST-EMB).

4 Application of this methodology to heavy rainfall events in Catalonia

Once all the 5-min rainfall series were analysed for the period 1996–2000, 43 heavy rainfall events were found. Approximately, 70% of the heavy rainfall events were produced

Table 4. Main seasonal features of the heavy rainfall events recorded in the Internal Basins of Catalonia for the period 1996–2000.

	Total event (mm)	Daily (mm)	Hourly (mm)	5-min Rain Rate (mm/h)	N. Events
DJF	214.6	115.0	37.1	97.4	8
MAM	120.4	85.8	43.1	108.6	6
JJA	110.5	79.3	56.2	140.5	14
SON	154.1	115.0	62.8	161.5	15

Table 5. Seasonal distribution of precipitation structures.

	MCS-LS	MCS-TS	MCS-CLU	MCS-NS	MUL	IND	EST	EST-EMB
DGF	1	0	4	1	7	4	3	4
MAM	0	0	2	2	8	4	0	1
JJA	1	4	10	2	18	11	2	3
SON	3	7	13	7	24	13	0	8
Total	5	11	29	12	57	32	5	16

in summer (June–July–August) and autumn (September–October–November), but it is important to bear in mind that a significant number of cases were observed in all the seasons (e.g. 5 events in winter, the season with the least number of cases). Table 4 shows the seasonal average values of cumulated precipitation for 5 min, 1 h, and 24 h and for the complete event. Besides this, the total number of heavy rainfall events recorded in each season during the period 1996–2000 is also included.

This table shows clearly the different features of those heavy rainfall events. Winter is the season with the longest events and maximum cumulated rainfall either for the entire event or for 24 h. However the hourly and 5–min rainfall rates are the lowest. On the contrary, the summer events record the minimum values of cumulated rainfall for the entire event and for 24 h, but high values for 1 h and 5 min intervals. The spring events do not show very high precipitation values, not for the entire event neither for shorter time intervals. Finally, the autumn events record the maximum cumulated rainfall values for the 5 min, 1 h and 24 h intervals. All those features joined to the frequency of heavy rainfall events recorded in each season point to autumn as the most dangerous season and to spring as the least dangerous one. Although not all heavy rainfall events can produce floods, the climatic analysis of floods recorded in Catalonia since the 14th century corroborates that autumn is the season with the maximum flood risk (Llasat et al., 2003).

A total of 167 main precipitation structures associated to 31 heavy rainfall events have been identified. Table 5 shows that MCSs and Multicells are the most common structures, with a frequency of 57 cases, followed by Individual cells, that has been found as maximum responsible of heavy rainfall events in 32 occasions. The Cluster structure is the most frequent between the MCS cases (more than 50%). Although it is possible to record the MCS structures in any season of the year, they are mainly produced during the autumn season. This seasonal feature is observed in all the precipitation structures with the exception of those stratiform ones that have their maximum frequency in winter. However, the contribution of both structures dominated by the stratiform field is low (only 21 cases) due to the fact that high intensities are related to convective rainfall.

Although 45 non MCS structures in front of 30 MCS structures have been found on the heavy rainfall events recorded in autumn, flood events are usually associated with MCS structures in which high rainfall rates can last some hours. The mean daily rainfall recorded when a MCS has been detected is 89.7 mm, being the maximum registered during the analysed period of 223.0 mm. Only multicells and convection embedded in stratiform regions can sometimes attain rainfall values as high as those typical of MCS.

For the complete volume of radar imagery approximately 13 000 convective cells have been identified. In general, Z_{max} values lie (67% of cases) between 38 and 49 dBz, which can be considered as the thresholds for "normal" cells, with a minimum value of 31.5 dBz and a maximum of 68.5 dBz. Weak cells (with $Z_{max} < 38$ dBz) have occurred in only a 21% of cases, meanwhile intense cells (most of them associated to hail) have occurred only in a 12% of cases. The relationship between Z_{max} and volume is not a proportional one. Then, the most intense cells usually do not have the greatest size. The last point analysed has been the duration of the cells. In general (near of 60% of cases), the life-cycle does not exceed 30 min, and only for a few cases ($<5\%$) the duration of the cell is equal or greater than 2 h.

Four mesoscale convective systems (Fig. 6) have been selected as examples of the classification proposed in Sect. 3.5. Two of them occurred on 14 September 1999, and are an example of the LS and NS types. The other two were produced between 9 and 10 June 2000 and are an example of the TS type. Although it was produced during the spring season, this last event showed the typical autumn features (Llasat et al., 2001). The maximum daily cumulated rainfall registered was 116.6 mm for the first event and 223.8 mm for the second

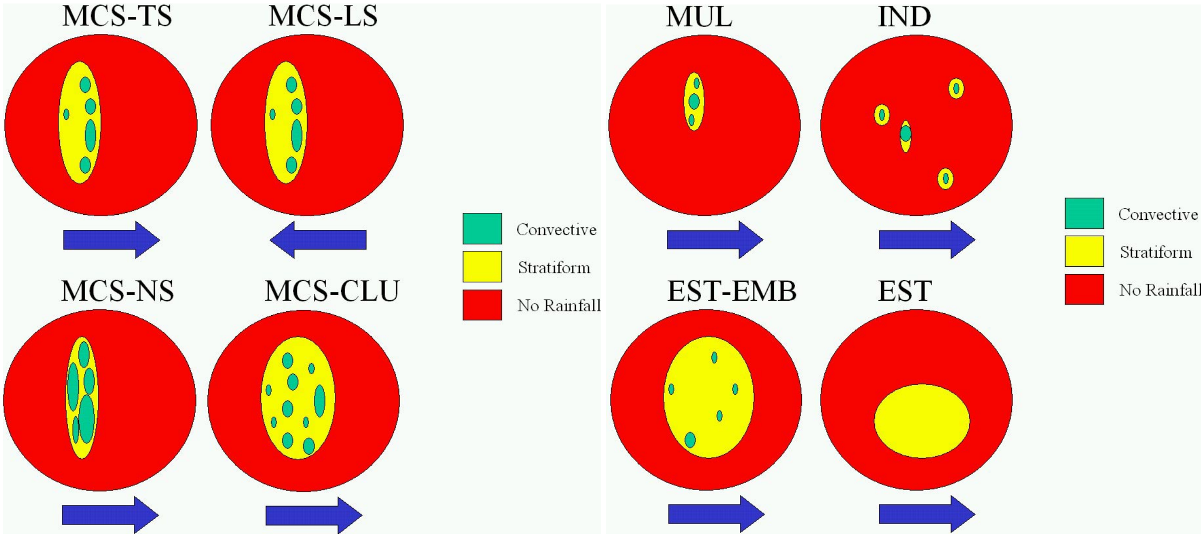

Fig. 5. Classification of: **(a)** mesoscale convective systems, **(b)** cloudy structures not considered as mesoscale convective systems.

Table 6. Mean values of the features obtained for four MCS 2-D structures.

Structure	Orientation (°)	Greater axis (km)	Smaller axis (km)	Motion (km/10 min)	Direction (°)
1	86.5	209.5	192.0	7.6	45.0
2	45.0	229.3	94.1	4.9	40.0
3	50.0	209.5	94.4	5.8	35.0
4	67.5	179.8	94.8	9.7	57.0

one (which represents the maximum value recorded during the period analysed).

Table 6 shows the mean values for the size, the shape and the motion of the MCS (numbers refers to Fig. 6). It is important to note that, due to the blockage effect produced by the lineal convective area, the stratiform region is not well detected, especially in the rear part of the most active zone. This negative effect in the analysis can be observed in all the MCSs presented. All the structures have a similar direction (from SW to E), which is the most common of the MCS that usualy affect this region (Martín et al., 1998). One factor that can explain the differences between the cumulated rainfall values of the two events studied (on June 2000 the value is nearly twice greater than on September 1999) is the velocity of the MCSs: meanwhile on June 2000, the speed was close to 5 km/10 min (this is, 30 km/h), on September 1999 it was approximately 8.5 km/10 min (50 km/h). Besides this, this last structure moved with a constant speed, while on June 2000 both systems remained stationary over the same place with a translation speed near zero. The analysis of the 3-D structures shows that for the June event the cells were moving in a direction tangential to the MCS, while for the September event the displacement was parallel to the movement of the 2-D structure. This is another aspect to consider in explaining the amount of precipitation registered: for the second case the convective cells passed over a point for a brief period, meanwhile in the first event the effect known as convective train was dominant (cells precipitate repeatedly over a same point).

5 Conclusions

The high number of heavy rainfall events in Catalonia has led to a need to obtain a methodology to classify them on the basis of their rainfall distribution at the surface, their internal organization and their physical features obtained from the meteorological radar. The main goal of this work has been to carry out a methodology to study precipitation structures (2-D and 3-D) that usually affect the region. At present it has been used to identify and classify those structures related to heavy rainfall events. With this aim, data from 126 automatic tipping buckets and from the meteorological radar of Barcelona (NE part of the Iberian Peninsula) have been considered.

The methodology has been applied so far to 43 cases of heavy rainfalls. Approximately 70% of these heavy rainfall events were produced in autumn and summer. The autumn events recorded the maximum cumulated rainfall values for the 5 min, 1 h and 24 h intervals. Although for the period 1996–2000, winter was the season with the longest events and maximum cumulated rainfall for the entire event, previous analysis shows that values above 400 mm were recorded in some heavy rainfall events produced in the autumn (i.e.

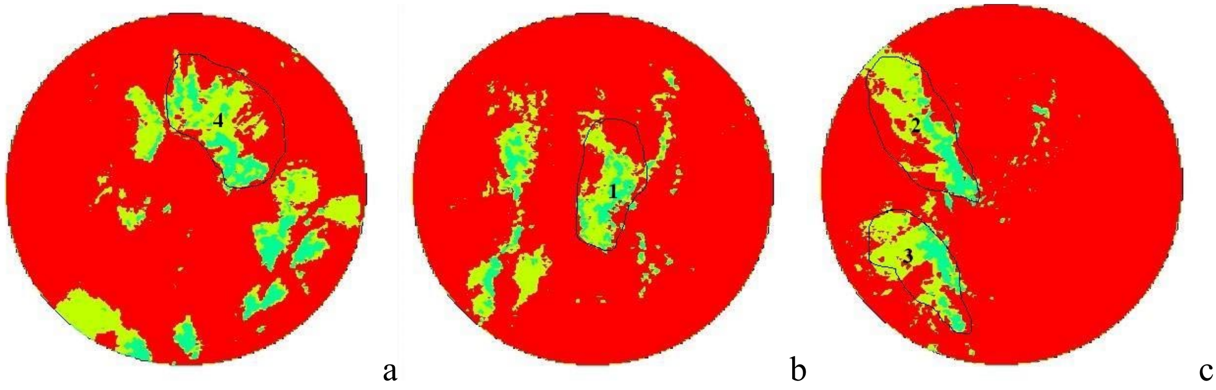

Fig. 6. Example of four linear mesoscale convective systems **(a)** and **(b)** are LS and NS cases, respectively (14 September 1999), and **(c)** are two TS cases (10 June 2000). Green areas are "convective" rainfall regions, while yellow means "stratiform" rainfall.

510 mm between 6–8 November 1982 or more than 700 mm between 17–19 October 1940).

A classification of precipitation structures has been proposed. This classification distinguishes between Mesoscale Convective System (MCSs), Multicell systems (MUL), Isolated convection (IND), Convection embedded in stratiform rainfall (EST-EMB), and Stratiform (EST). MCS structures can be classified depending on the relative position of its stratiform region and depending on the organization of the convective region in: well-organised systems usually lineally, called TS (with rearing stratiform area), LS (leading stratiform region), and NS (with practically non stratiform precipitation) and clusters of convective structures (CLU). The supercell structures have not been considered here because Doppler wind information is required. A total of 167 main precipitation structures associated with 31 heavy rainfall events have been identified. MCS and Multicells are the most common structures, with a 57 cases in each category, followed by Individual cells (32 cases). The Cluster structure is the most frequent among the MCS cases (more than 50%). Although it is possible to record all the structures in any season of the year, they are mainly produced during the autumn season. Exception is identified for the stratiform structures, not recorded in either spring or in autumn.

For the complete volume of radar imagery approximately 13 000 convective cells have been identified. In general, Zmax values lie (67% of cases) between 38 and 49 dBz, which can be considered as the thresholds for "normal" cells, with a minimum value of 31.5 dBz and a maximum of 68.5 dBz. The most intense cells usually do not have the greatest size. For 60% of cells, its life-cycle does not exceed 30 min, and only for a small number of cases ($<5\%$) the duration of the cell is equal to or greater than the 2 h.

The specific analysis of 4 MCSs structures shows the importance of the system stationarity for the value of accumulated precipitation recorded in surface. This displacement along the MCSs life is closely related to both the wind speed in mid-troposphere and to the movement of individual cells into the convective system.

Future work will involve the creation of a complete climatology of the exceptional structures and to develop a procedure for short-range forecasting (at least 1 h) of those structures. This characterization is more difficult for the 3-D structures, due to the fact that there are more parameters than in the 2-D analysis, and there are a great number of cells in each image. Future research should thus contemplate the analysis of these parameters in order to obtain the most significant ones. The ensemble analysis of the climatological features with the nowcasting procedures will allow improvement of this last aspect. On the other hand, the 3-D procedure imposes the threshold of an extension of the convective pixels of 24 km^2 on more than one level. This situation, in combination with the movement of the cell, helps to avoid ground errors of the radar. However, others errors, like anomalous propagation, should be corrected in the future.

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